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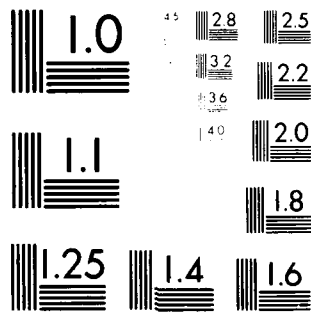
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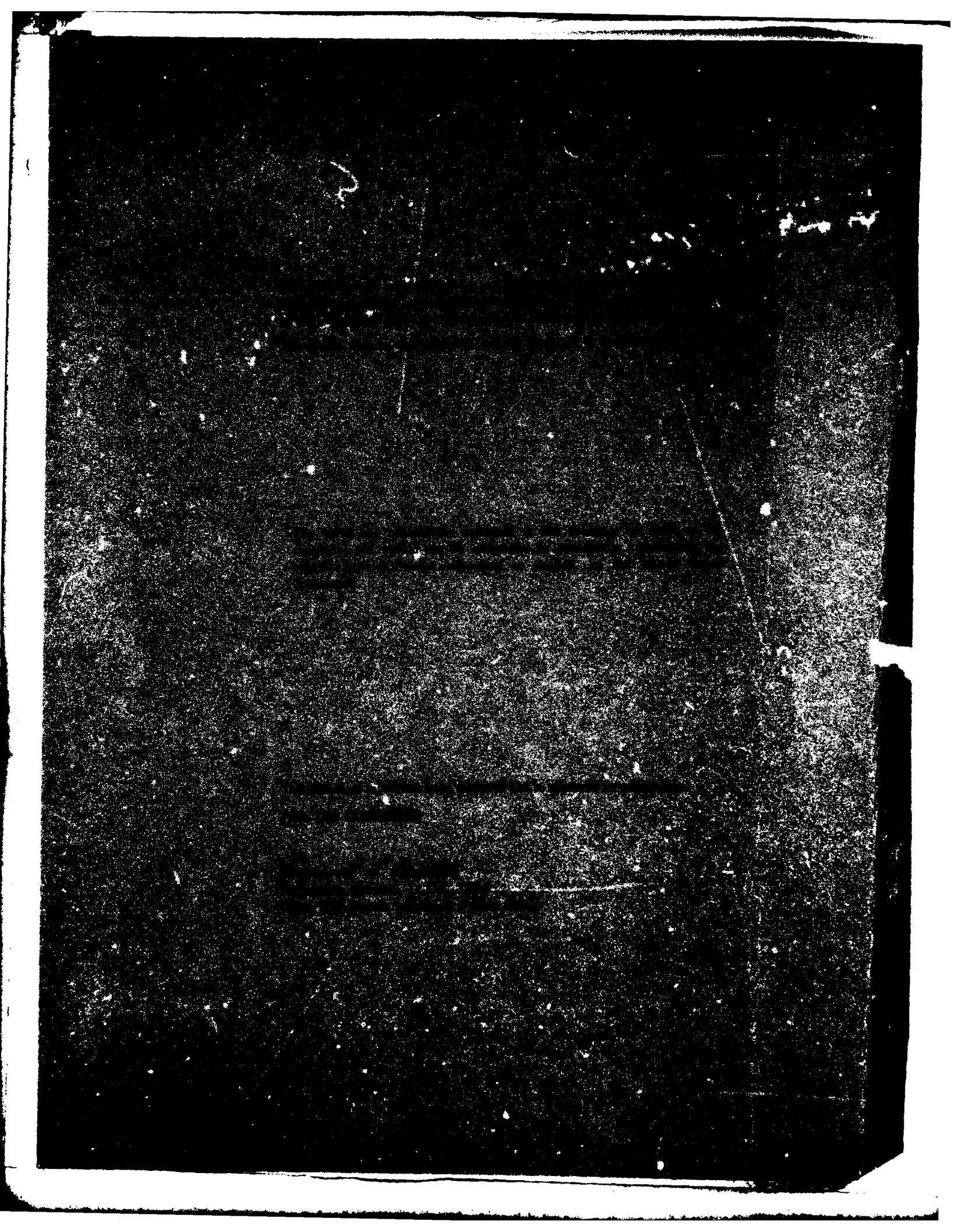
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LINCOLN LABORATORY

AN ANALYSIS OF FOLIAGE EFFECTS
ON LONG-RANGE SURVEILLANCE

D. L. HOGAN
Group 46

TECHNICAL NOTE 1980-9

23 APRIL 1980

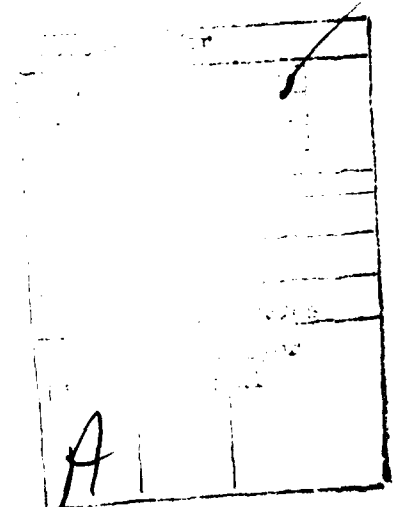
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ABSTRACT

This report adds perspective to the problem of foliage shielding. Measurements were taken at four locations along three major eastern Massachusetts highways. Analysis results are compared with data from Multiple Antenna Surveillance Radar (MASR) tests. Probability of clear line-of-sight and period of target visibility are the major topics addressed.



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I. INTRODUCTION

Visibility is one of the key factors in determining the outcome of battles. With the advent of long-range, moving target, air-to-ground surveillance radars, the motion of both the observing platform and the target have added to the visibility problem, which heretofore was analyzed in terms of shielding. The interaction of such factors as the minimum detectable velocity of the target, the trajectories of the target and the airborne radar platform, and the terrain and foliage masking combine to control the amount of time which a target is observed in a given scenario. This report continues the work done on dynamic masking^[1], compares the masking calculation with and without foliage on a typical super highway in New England, and finally examines the correlation between predicted and observed foliage and terrain masking.

The work was done in connection with the test and evaluation of the Multiple Antenna Surveillance Radar (MASR), a scaled model of a long-range moving target surveillance system. MASR operated at L-band with a beamwidth of approximately 4.5° . In typical flight operation it observed the target complex from a range of 25 to 40 km. The altitude was selected to give lookdown angles ranging from 3° to 6° . This geometry is similar to that of a high altitude platform as indicated in the accompanying sketch (Figure 1). Despite the long wavelength, there is no effective penetration of foliage at L-band so that the masking effects observed are similar to those which are obtained at shorter wavelengths.

Rather than rely on estimates of line-of-sight obscurations made from vertical aerial photographs and hypsographic data, photographs of the roads were made and clear line-of-sight versus elevation angle was derived. Section II of this report describes the technique for data collection. Section III describes the analysis of the photographic data and gives the results of analyses of specific scenarios.

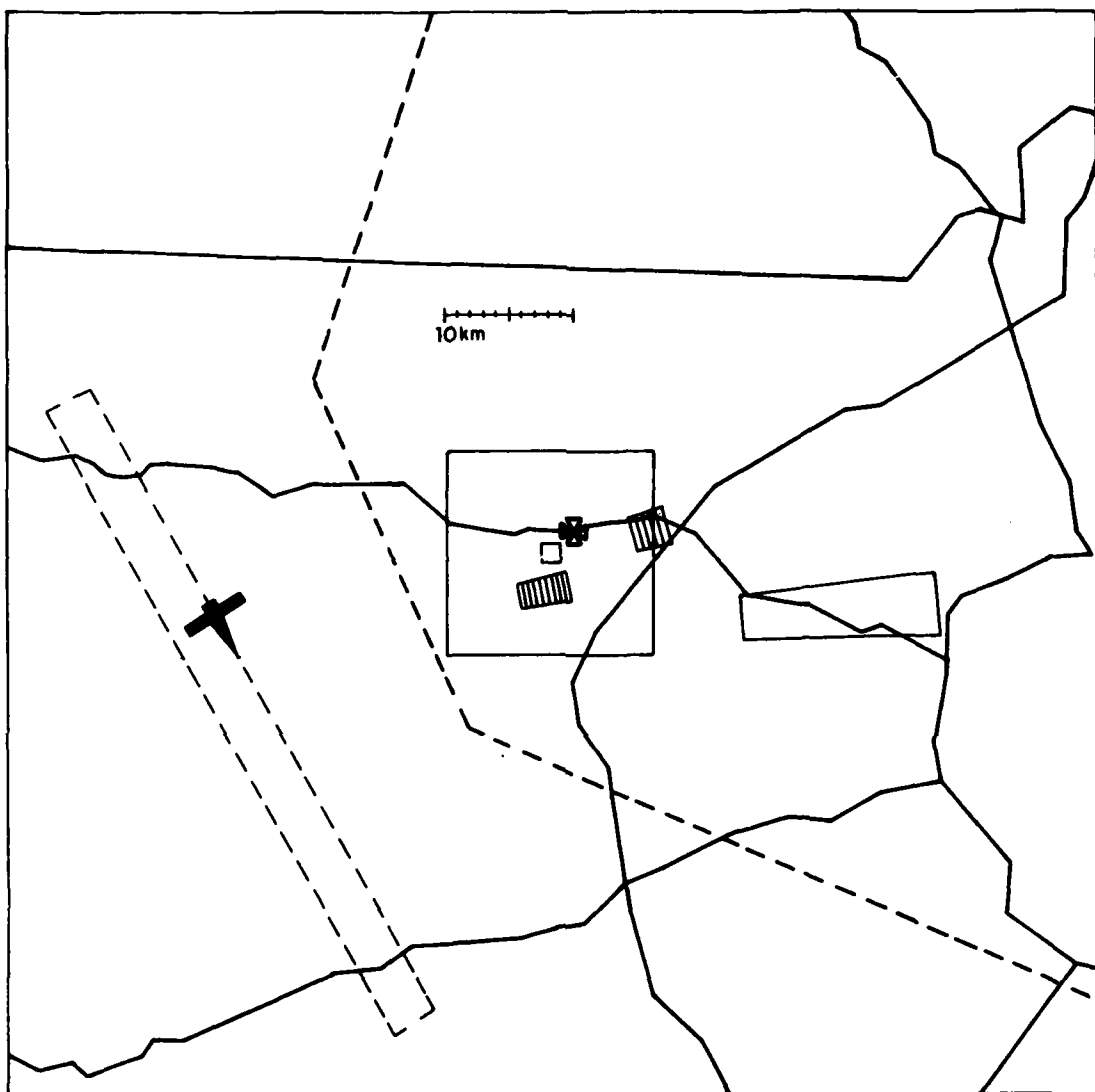


Fig. 1. Typical flight pattern for MTI surveillance.

II. DATA COLLECTION

To date, prediction of foliage shielding has been approached in the same manner as prediction of terrain shielding. Considering radar altitude and range to target area, visibility is determined by whether the elevation of objects between the radar and target is high enough to cause masking. C. Burge and J. Lind of the Naval Weapons Center at China Lake, California published a line-of-sight handbook^[2] examining terrain and vegetation masking. Their work presents probability of clear line-of-sight (LOS) models for twelve different terrain/vegetation types, ranging from deserts with little or no vegetation to sharply rolling hills with dense forest. As is done in terrain shadowing, Burge and Lind consider the probability of clear LOS over a large area.

The purpose of this study is to examine foliage effects on radar line-of-sight to a localized target area. Figure 2 is a photograph taken of the Massachusetts Turnpike near Framingham. If the automobile in the lower right of the picture is assumed to be approximately 1.5 m in height, then the average tree height would be about 15 m with only a meter or two between trees. It is unlikely that ground vehicles would attempt to pass through such dense forest. Analysis of foliage effects was focused on those areas where ground activity is likely to occur, particularly, primary and secondary roads.

Foliage would not be expected to have a great effect on surveillance of primary and secondary roads, since land is usually cleared when roads are constructed. Figures 3, 4 and 5 compare shielding due to terrain only and shielding due to both terrain and foliage for 3 portions of major highway in eastern Massachusetts. These figures show that even when terrain shadowing is minimal, foliage shielding can be significant.

For the purpose of application of results presented here, it should be noted that the geographic characteristics of eastern Massachusetts are similar to those of central Germany. V. L. Lynn collected data along



Fig. 2. Example of foliage height and density.

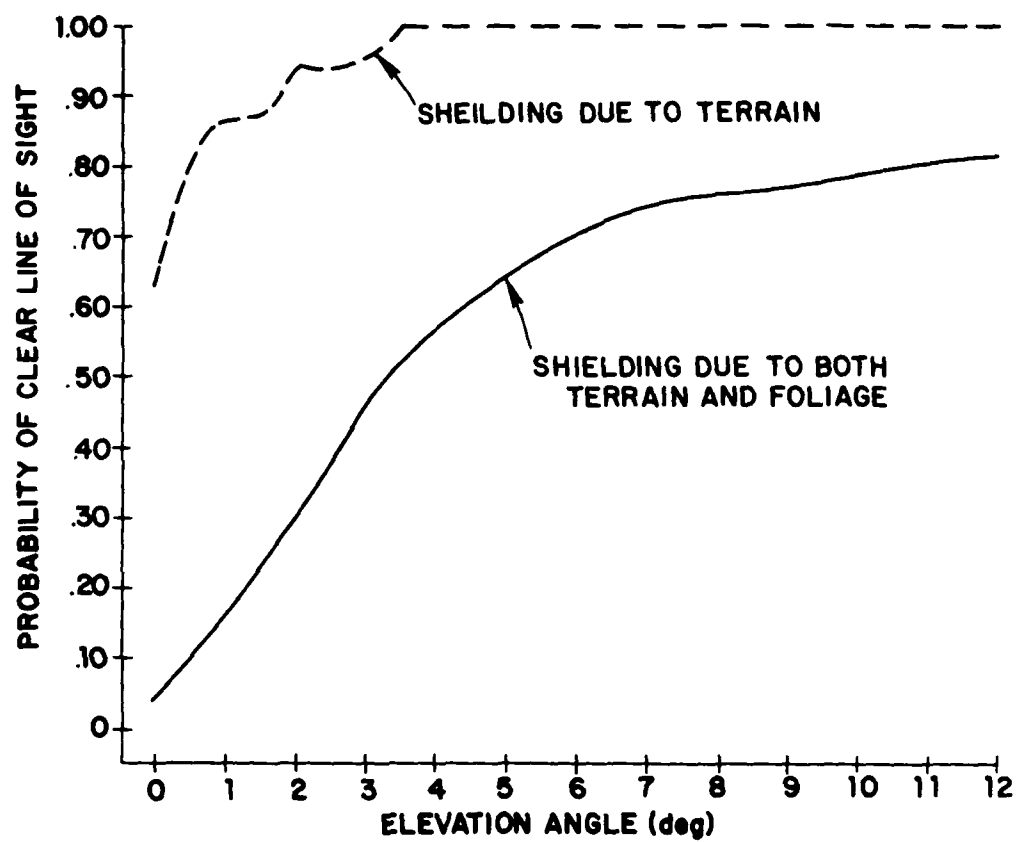


Fig. 3. Visibility vs elevation angle, Route 495.

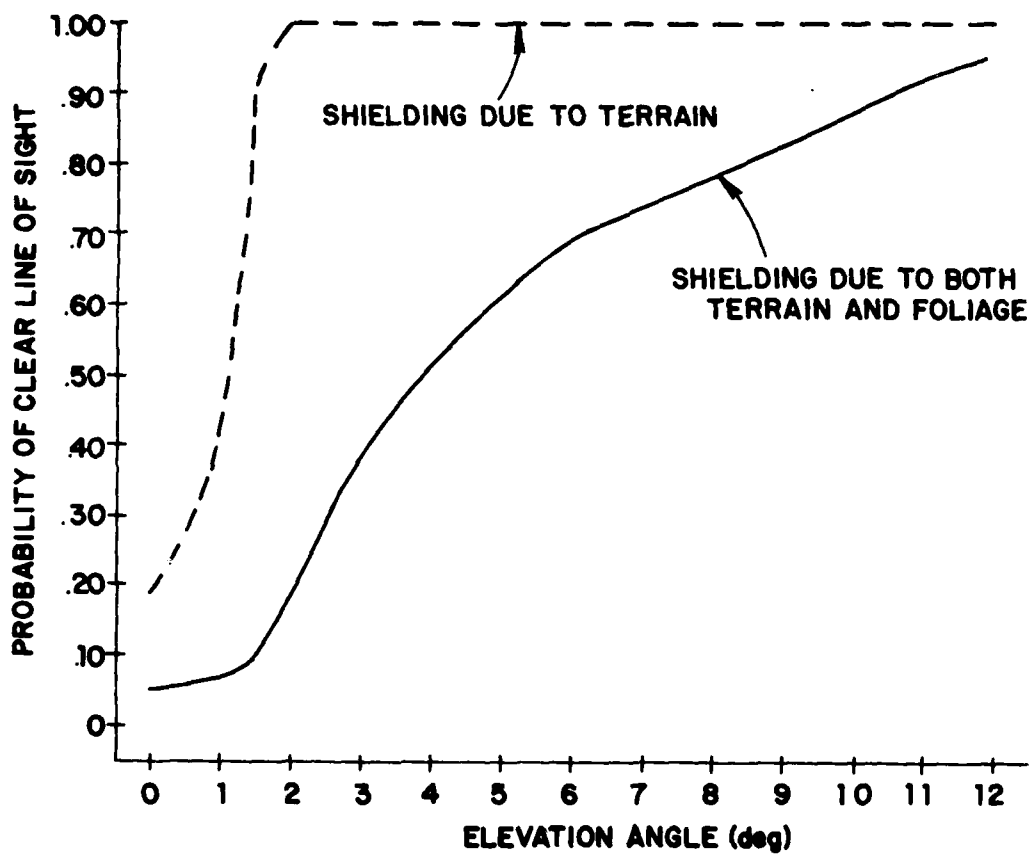


Fig. 4. Massachusetts Turnpike east, visibility vs elevation angle.

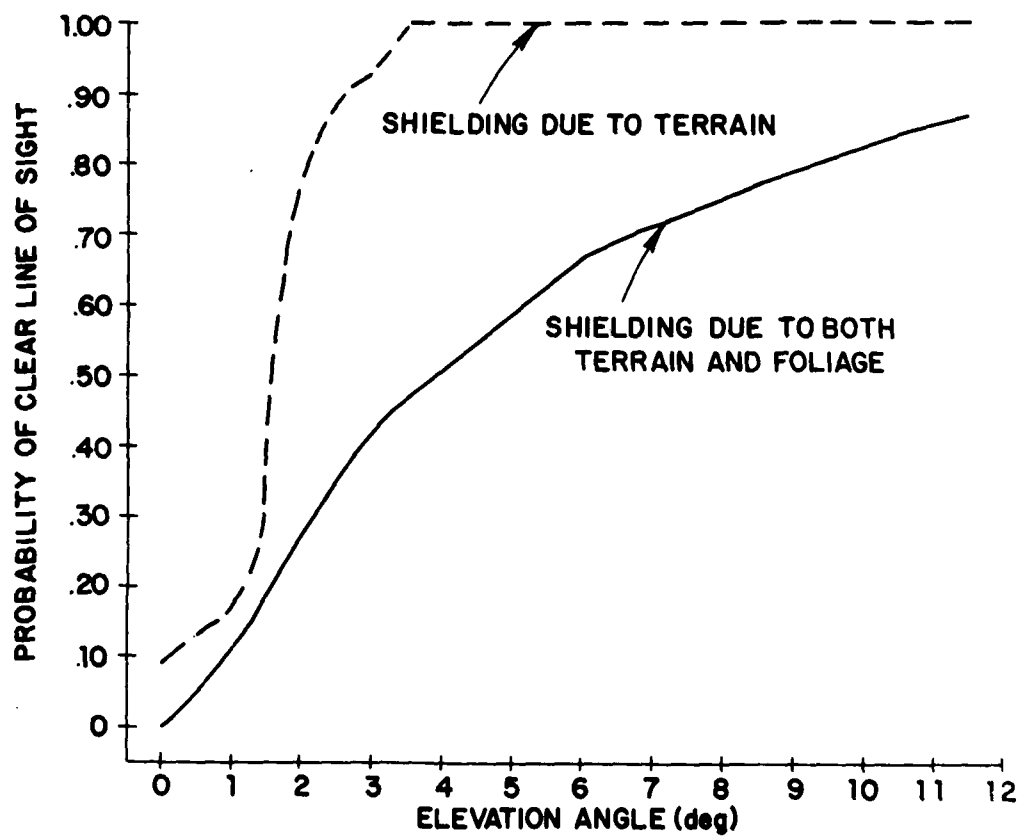


Fig. 5. Massachusetts Turnpike west, visibility vs elevation angle.

several major highways in the Fulda Gap region^[1] of Germany. For each measurement, the appropriate elevation angle* at which 50% visibility occurred was estimated. Lynn then determined periods of masking for each road and from those results derived a probability of clear line-of-sight versus elevation angle. His results are summarized in Table 1.

This report is similar to that done by V. L. Lynn. Although only 2.6 km of total road length is examined compared to Lynn's 90 km, this study examines a larger range of elevation angles. In addition, radar observations were correlated with successful hypsographic and foliage data.

Radar data collection for the selected roads was done during April and May whereas LOS data was collected in late summer. This difference may result in discrepancies due to diffraction or attenuation levels. However, for LOS evaluations, conditions can be considered identical**.

Figure 6 is a map of the area with the four test sites blackened and numbered. They are:

1 - Route 2

A 4.8 km stretch through Harvard, from .8 km west of the Boston and Maine Railroad underpass to .5 km east of the Poor Farm Road underpass.

2 - Route 90 (Massachusetts Turnpike -- east)

A 6.5 km stretch through Westborough and Framingham, from the Cordaville Road underpass to a point 1 km east of the Route 90 Worcester Road junction.

3 - Route 90

A 9.5 km stretch through Charlton and Auburn, from 4.6 km east of interchange 9 to .3 km east of the Merriam Road overpass.

*The angle above horizontal where the line-of-sight intersects the terrain; approximately, the angle of the line-of-sight below horizontal at the sensor.

**Neither diffraction nor attenuation was considered in this study. All data is in reference to target visibility due to obstructions in the line of sight.

TABLE 1^[1]

PERCENTAGE VISIBILITY

Based on a definition of the masking angle for any location as that depression angle for which clear line-of-sight exists for 50% of the azimuths within an "optimum" 38° sector

	Route E70	Route 84	Route 458	TOTAL ALL ROUTES
Length of roads measured (km)	32.5	25.1	30.7	88.3
Percentage Visible				
03°	30	40	61	45
06°	40	74	85	65



Fig. 6. Map of eastern Massachusetts showing selected roads.

4 - Route 495

A 3.8 km stretch through Westford, from the Great Road overpass to the Boston Road underpass.

The visibility was determined by measuring the elevation of the skyline over a wide range of azimuths. The analytical data were correlated with airborne radar observations. Photographs of the skyline profile were taken at several locations along each road.

Depending upon topography and foliage, intervals between photographs range approximately from 0.1 to 1.5 km. For example, if the road curved sharply, photographs were taken more frequently to characterize the rapid change in the skyline. Conversely, fewer photographs were taken when there was little or no change in the skyline over a long distance such as the case of either a forest or field consistently lining a stretch of road.

In order to duplicate the radar LOS, photographs were taken in the direction of the aircraft racetrack. Given that the camera field of view is 45° , rather than centering the photograph in the direction of the road, an effort was made to align the center of each photograph with the center of flight path for the MASR aircraft. The angle from the road to the center of the racetrack was precalculated. At each site the camera's field of view was centered on a reference at the proper angle to radar LOS.

A transit was used to measure elevation angles of objects in the field of view. At least two measurements per location were recorded for accuracy in scaling. The principal sources of error are:

- Accuracy of transit
- Horizontal tilt of camera
- Alignment of center reference

The transit was calibrated and found to be in error $\pm .23^\circ$ rms.

Tilting the camera would result in lower elevation angles to one side of the field of view and higher elevation angles to the other.

Error in aligning the reference for the center of the racetrack with the center of the photograph would result in elevation angle measurements being offset in azimuth.

The last two errors were compensated for in the data processing (see Section III). The overall error in measuring the elevation angle to the skyline is $\pm .23^\circ$ rms.

III. METHOD OF ANALYSIS AND RESULTS

As stated in Section II, each photograph contained two possible sources of error: A tilt in the horizontal level of the camera, and the 0° reference being located off-center.

If the camera had been tilted to one side, errors in skyline elevation would increase outward from the center. Since several measurements of elevation angle had been recorded for each photograph, a vertical linear scale could be determined. Using a scaled transparent overlay, each photograph was tilted an appropriate amount until the references corresponded to the proper grid lines of elevation. This method corrected any horizontal leveling error. The skyline was then traced onto the overlay, ignoring any isolated trees.

The center line reference was noted in each photograph and transferred to the tracing as 0° azimuth. The 0° azimuth mark represents the line-of-sight to the center of the racetrack. On each tracing a linear abscissa was marked with respect to the 0° reference, also re-aligning the reference and center racetrack. However, the center of the photograph does not necessarily correspond to 0° azimuth.

Figures 7 and 8 are an example of a photograph and its corresponding tracing. Both show the skyline for a location on Route 2 near the junction of Route 110.

The data from each location could have been digitized and put in a two-dimensional array so that for a given azimuth there would be a corresponding critical elevation angle*. It would then be possible to

*The critical elevation angle is that at which masking starts to occur.



Fig. 7. Sample of skyline photograph, Route 2.

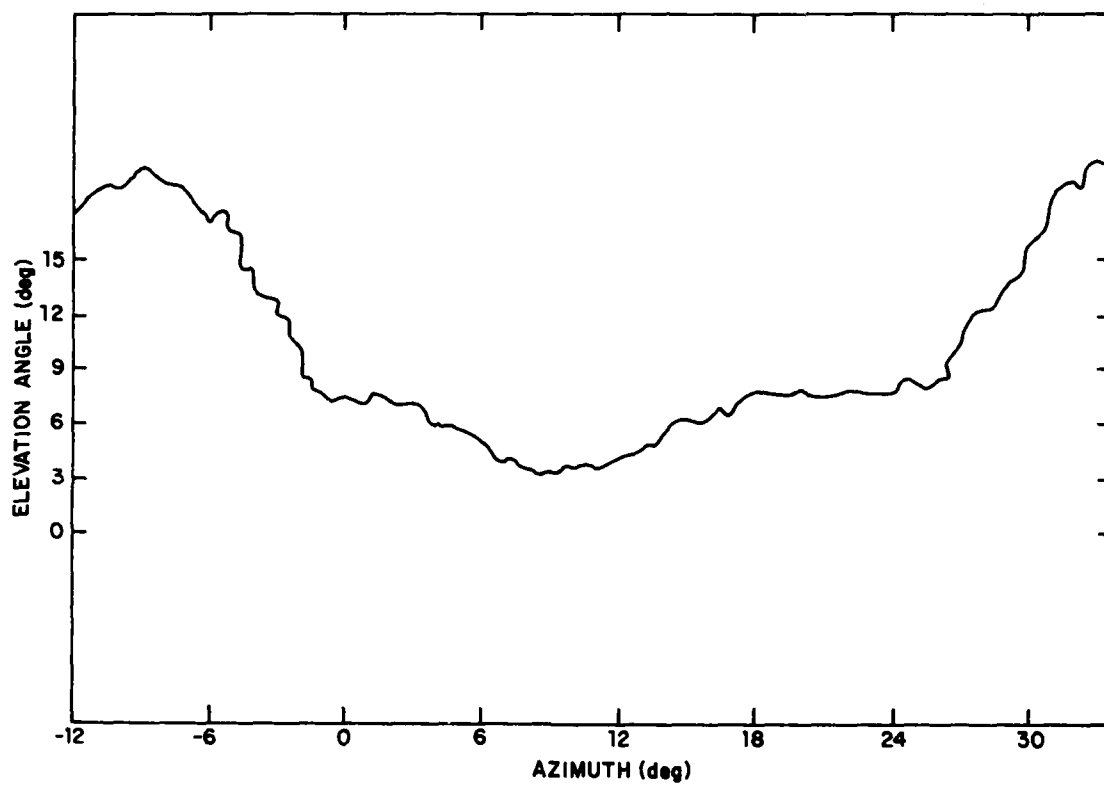


Fig. 8. Skyline profile corresponding to Fig. 7.

access the data base and know whether or not masking occurs for a given azimuth and elevation angle. However, in this investigation a simpler form of analysis was considered sufficient.

For visibility of the road (or probability of clear LOS) with respect to elevation angle, the main problem was to determine whether or not masking occurred at each azimuth for each photograph with respect to the elevation angle in question. This was done by using the skyline tracings as graphs. Reading across from the left for the azimuth and up from the bottom for elevation angle, a unique point is located. If the point lay above the critical elevation for that azimuth (i.e., that point was higher than the skyline) then a clear LOS was assumed for that azimuth/elevation. An average visibility was then calculated and the process repeated for elevation angles of 0° through 12° at 1.5° increments.

Figure 9 is a probability of clear LOS versus elevation angle for all the roads combined. Since the terrain/vegetation type is fairly consistent from location to location, the composite graph is generally representative of the area. A similar plot for each road is included in the Appendix. The elevation angle at which 50% of the observed road is visible is given in Table 2; it varies from 2.75° to about 4° . However, as Figure 9 shows, the average for this terrain/vegetation type might be .5 probability of clear LOS (i.e., 50% visibility) for an elevation angle between 3.25° and 3.5° . These figures are encouraging in view of the fact an elevation angle less than 4° is typical in long-range surveillance.

The relevant parameter for stand-off surveillance and strike is a target's period of visibility, since target tracking is often a primary factor in determining time and location of weapon delivery. Tracking parameters could be adjusted accordingly if it were known that a target was going to be shielded for some interval. For example, if sporadic visibility is anticipated, an increase in the size of the range association box would prevent a track from being dropped.

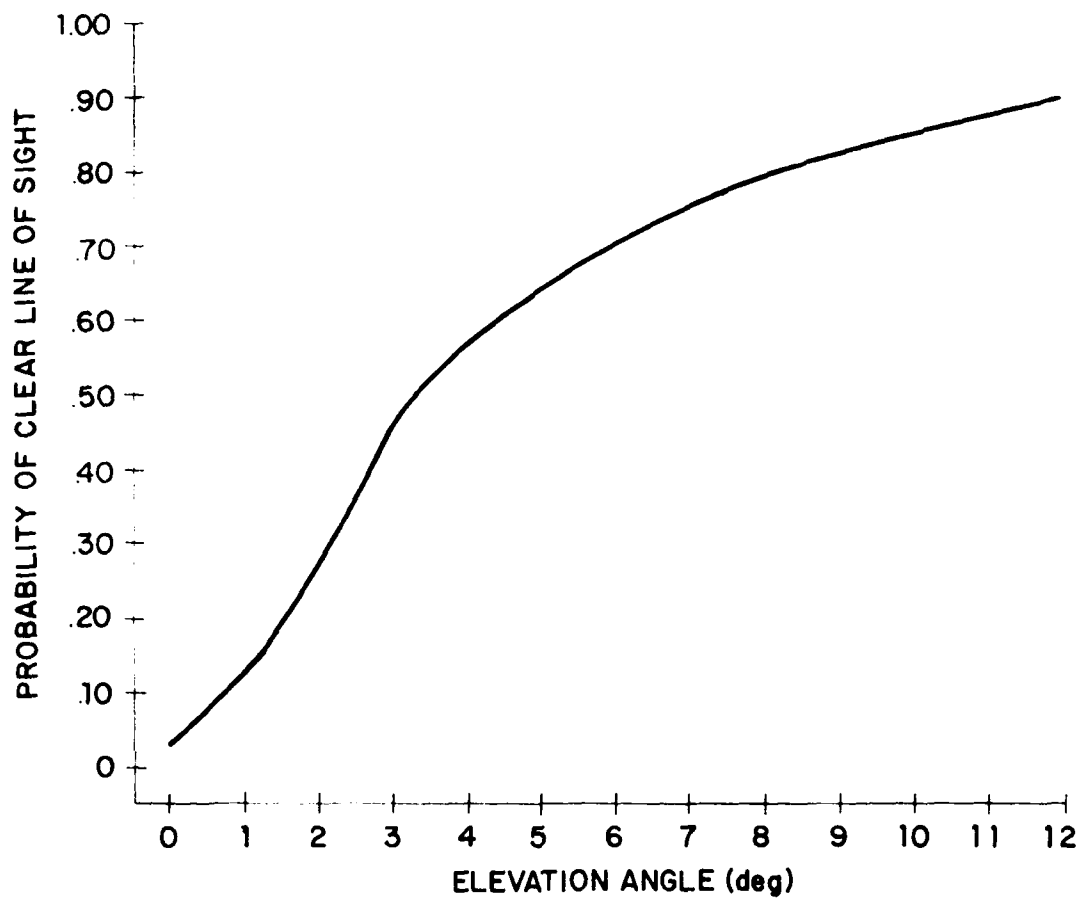


Fig. 9. Visibility vs elevation angle, all roads combined.

TABLE 2
REQUIRED ELEVATION FOR 50" VISIBILITY

Location	Elevation angle at which probability of clear LOS = .5
Massachusetts Turnpike east	3.9°
Route 2	2.75°
Route 495	3.25°
Massachusetts Turnpike west	3.8°

A scenario must be established in order to determine the period of visibility of a target from the photographic data. Different aircraft speeds and altitudes result in different periods of visibility. For comparison, three scenarios were developed; they are:

- A - A 450 mps aircraft at an altitude of 55 kft and a range to the target area of 150 km. The resulting depression* angle is 6° .
- B - A 250 mps aircraft at an altitude of 45 kft and a range of 213 km with a depression angle of 3° .
- C - A 250 mps aircraft altitude of 45 kft and a range of 98 km resulting in a 6° depression angle.

In each case, a ground vehicle was observed travelling along the selected road segment at 11.1 mps in first an easterly and then a westerly direction. The duration of observation is dependent upon the total travel time of the vehicle. The time required by the ground vehicle to travel the length of the road segment had to be less than or equal to the time of observation by the aircraft. Table 3 summarizes the criteria for each scenario and road. Figure 1 shows the Route 2 target area and a possible orbit for the surveying aircraft. The usual mode of observation would be to overlap range windows in some pattern over an area, similar to the pattern shown by the overlapping rectangles in the center of Figure 1. However, in the scenarios presented here, range windows progress along the road at exactly the same rate and in the same direction as the ground target.

Since line-of-sight and, hence, masking is a function of 2 variables, the location of the aircraft and the location of the vehicle, their combinations must be considered. Visibility was determined for both eastbound and westbound vehicles. The results differ because of the difference in the line-of-sight traversing the screening hills and foliage. A given ground location is not observed from the same air location.

*Recall that depression angle is equivalent to elevation angle.

TABLE 3

SCENARIO PARAMETERS

Road	Road Length	Total Time	Data Leg Length	Aircraft Altitude	Elevation Angle	Range to Target Area
Route 2	4.8 km	7.21 min	108 km	45 kft	3°	213 km
					6°	98 km
			172 km	55 kft	6°	150 km
Route 495	3.74 km	5.62 min	84 km	45 kft	3°	213 km
					6°	98 km
			135 km	55 kft	6°	150 km
Mass Pike east	6.5 km	9.76 min	146 km	45 kft	3°	213 km
					6°	98 km
			234 km	55 kft	6°	150 km
Mass Pike west	9.5 km	14.27 min	214 km	45 kft	3°	213 km
					6°	98 km
			342 km	55 kft	6°	150 km

Figures 10-21 are plots of visibility versus elapsed time for each of the roads. On each graph is the selected road and scenario, direction of travel, road length, total elapsed time, and percent of the pass for which the vehicle was visible (related to probability of detection). Occasionally, the skyline tracings did not extend far enough in azimuth. If at either edge of the picture the trend for the skyline seemed to be higher than a 6° elevation angle, masking was assumed for azimuths outside the field of view. These extrapolations are represented by dashed lines.

In general, these figures indicate that periods of masking vary greatly from location to location and depend on the direction of travel. The Massachusetts Turnpike west has long periods of visibility or invisibility while Massachusetts Turnpike east has shorter periods. As can be seen in the graphs for Routes 2 and 495, a west-east travelling vehicle is nearly constantly visible, yet a vehicle travelling east-west generates poor results.

A scenario which is consistent from location to location allows for comparison of visibility models. However, it prevents exact matching of actual radar data with predicted results. Variables such as effects of wind speed and direction, pattern of ground observation, and aircraft deviation from the flight path were not considered when constructing visibility models. For some of the MASR data, though, a general comparison is possible.

Figure 22 is a range vs time plot of raw target reports. The diagonal lines are vehicles moving in both directions on Route 495, a divided highway. The hyperbolic-shaped track is the Moving Target Simulator (MTS), a stationary transponder used as ground reference point during MASR testing. The shape of its track is due to aircraft motion. A cluster of vehicles can be seen moving from the lower left to the upper right (west-east). These reports represent a convoy of 9 vehicles --- seven busses and two police cars. The tracks are visible almost continuously over 6 minutes.

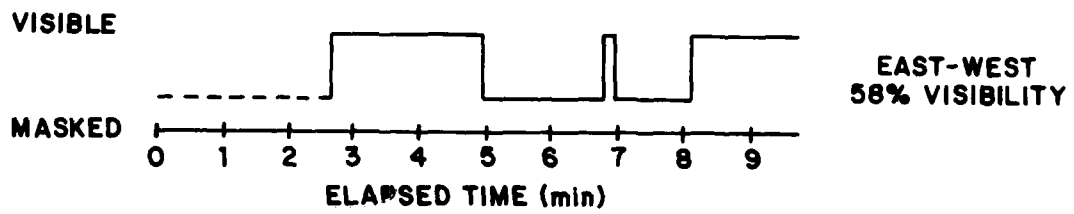
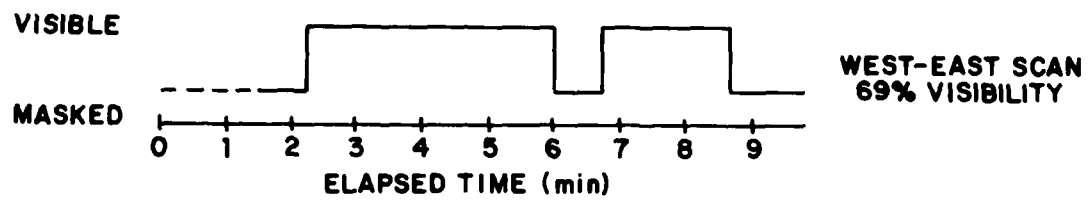


Fig. 10. Massachusetts Turnpike east scenario A.

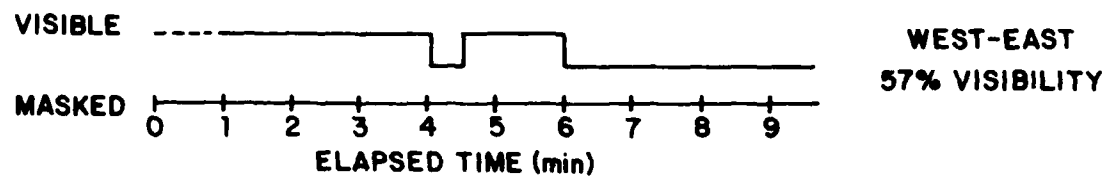
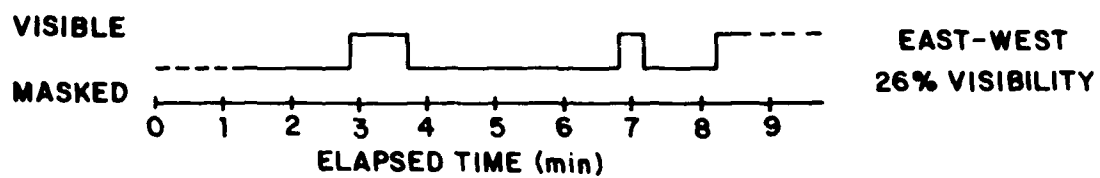


Fig. 11. Massachusetts Turnpike east scenario B.

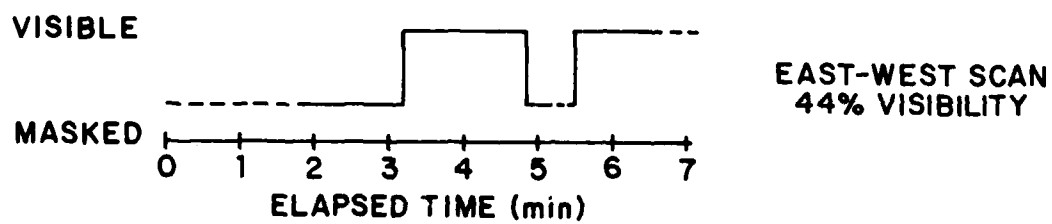
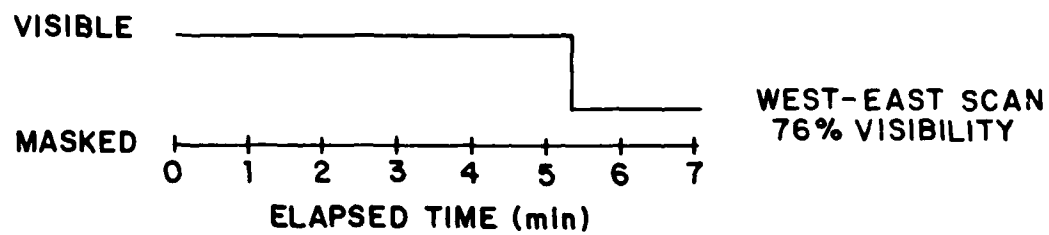


Fig. 12. Route 2 scenario A.

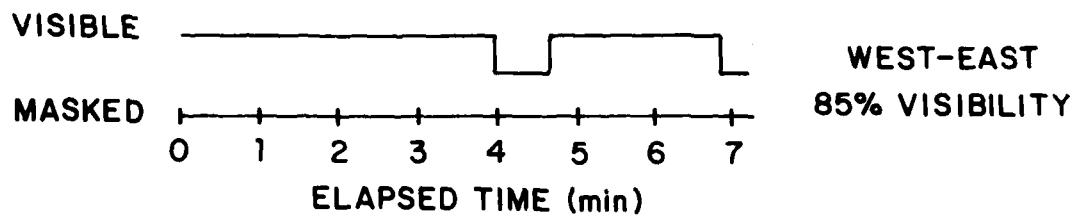
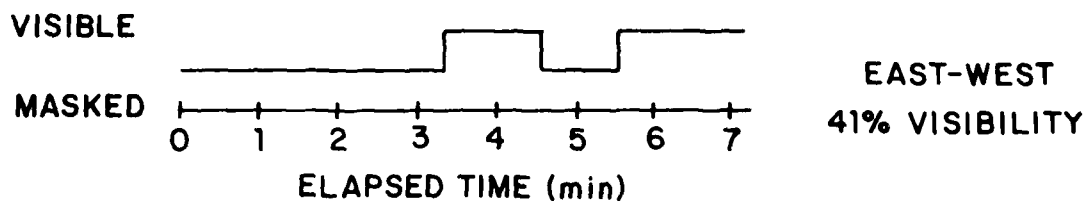
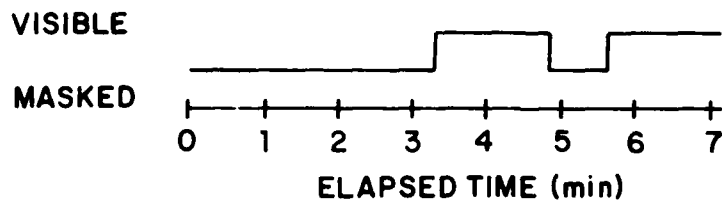
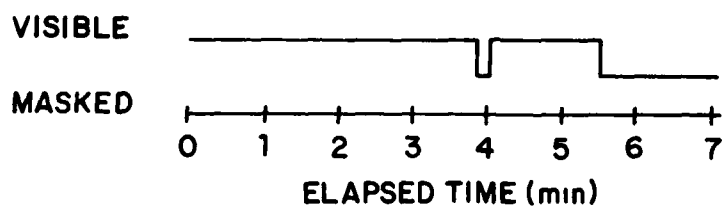


Fig. 13. Route 2 scenario B.



EAST-WEST
44% VISIBILITY



WEST-EAST
75% VISIBILITY

Fig. 14. Route 2 scenario C.

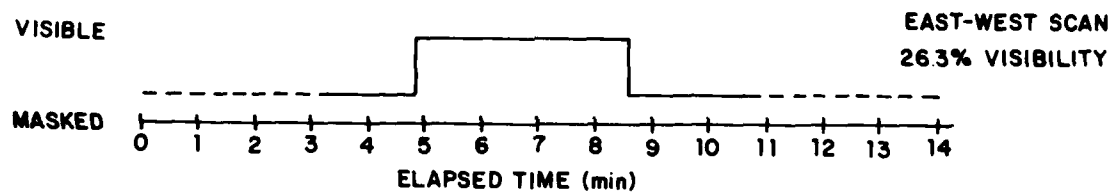
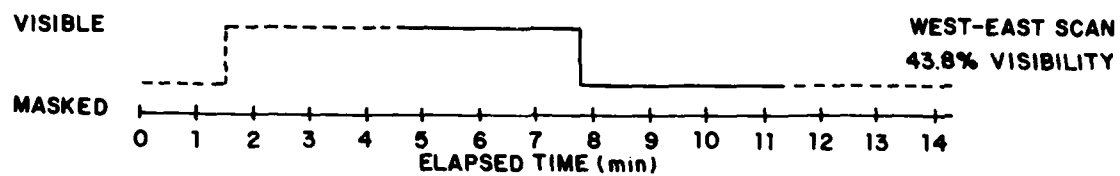


Fig. 15. Massachusetts Turnpike west scenario A.

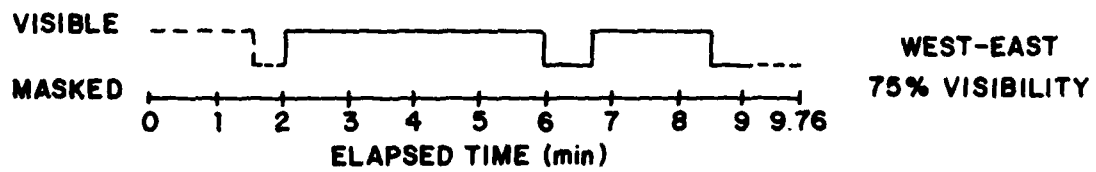
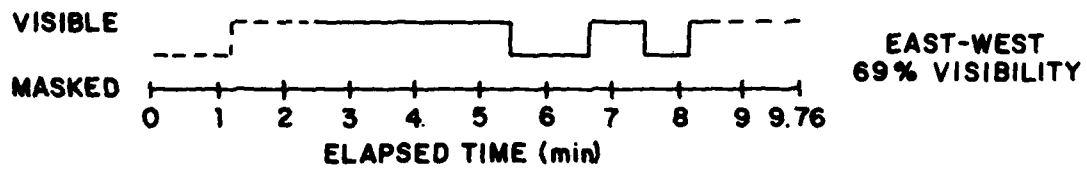


Fig. 16. Massachusetts Turnpike east scenario C.

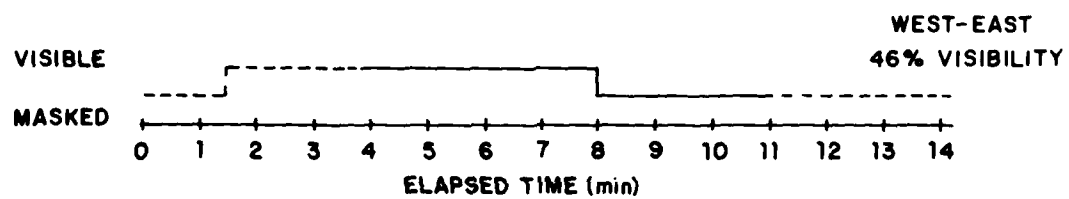
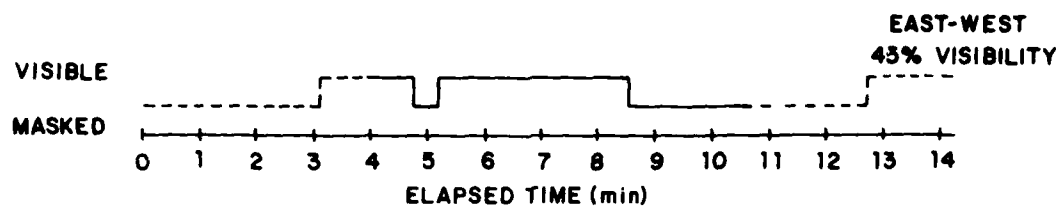


Fig. 17. Massachusetts Turnpike west scenario C.

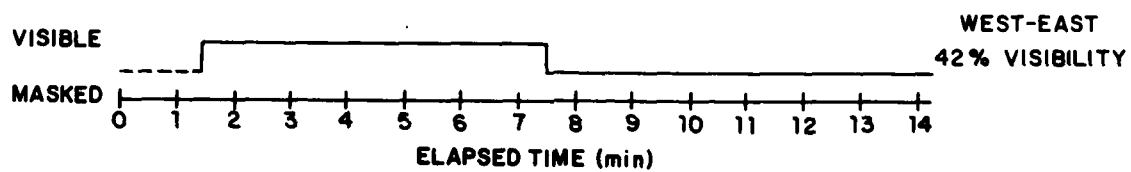
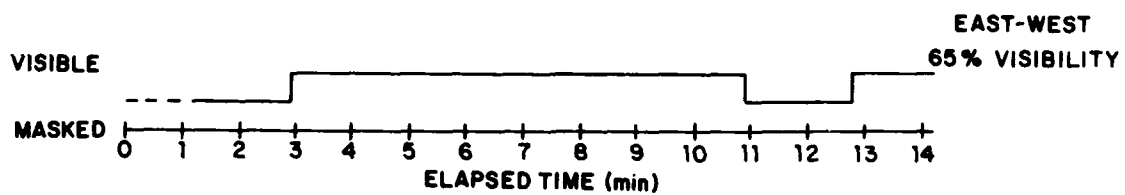


Fig. 18. Massachusetts Turnpike west scenario B.

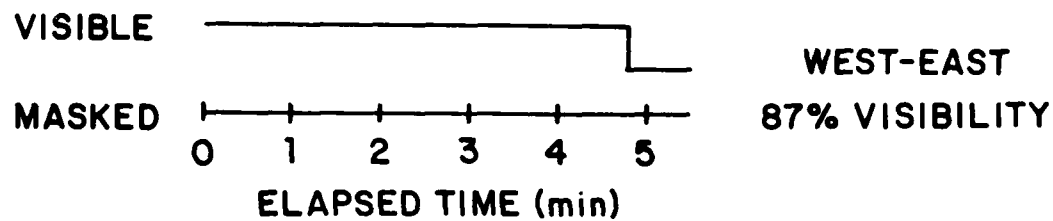
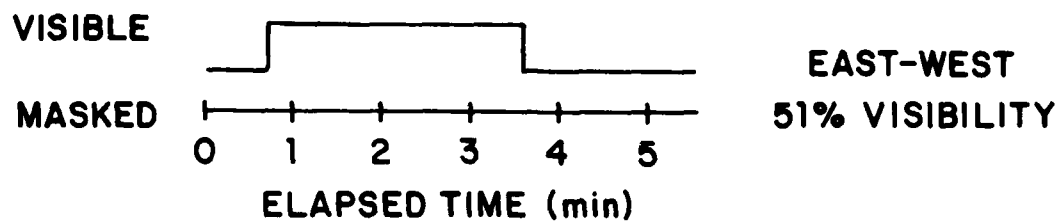


Fig. 19. Route 495 scenario C.

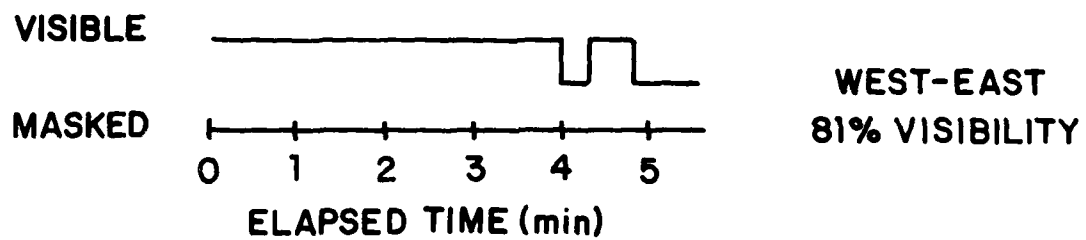
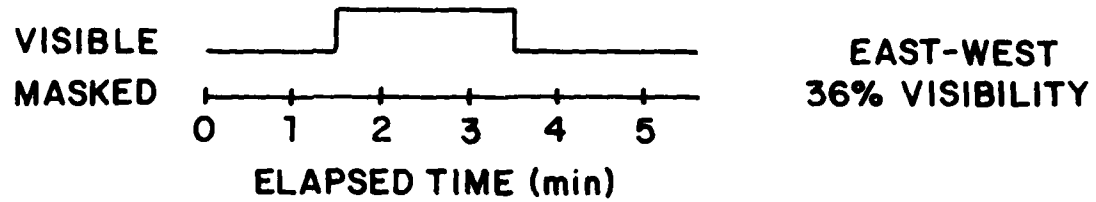


Fig. 20. Route 495 scenario B.

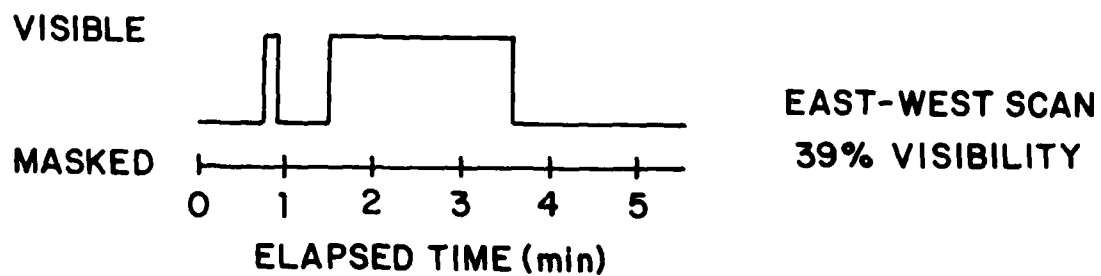
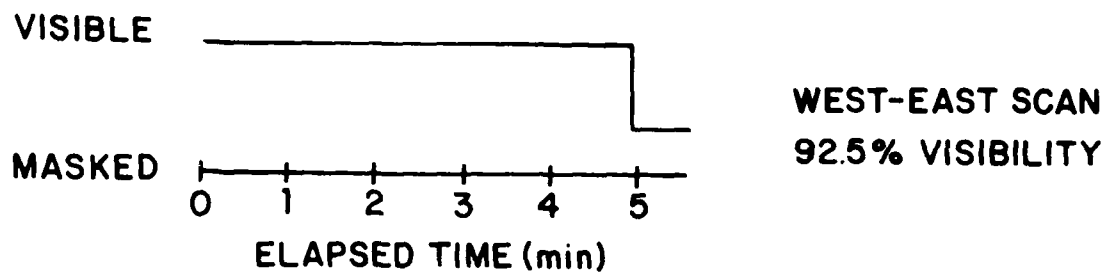


Fig. 21. Route 495 scenario A.

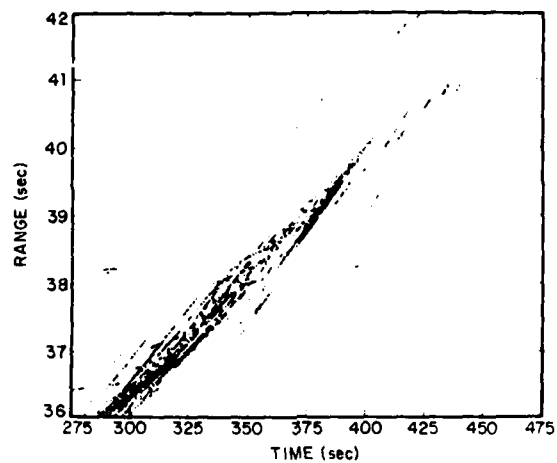
Comparing this data to the expected visibility of Route 495 when scanning west to east (Figure 21), a correlation is evident. The dropouts in Figure 22 at approximately 6 minutes into the pass correspond to the masking at approximately 5 minutes elapsed time in scenario A.

Overall, predicted periods of masking range from 30 seconds to over six minutes. Obviously, maintaining track on a target that remains invisible for over six minutes poses a problem. Although this may seem disheartening, the purpose of anticipating foliage shielding is not to discourage the use of long-range radar but instead to focus attention on a major problem so that it can be dealt with. If a period of invisibility is expected, corrections may be made to the aircraft's flight path to compensate. All that might be needed to regain target visibility would be a several hundred foot increase in altitude. Or, possibly, adjustments to aircraft speed might favorably alter or even eradicate a period of masking.

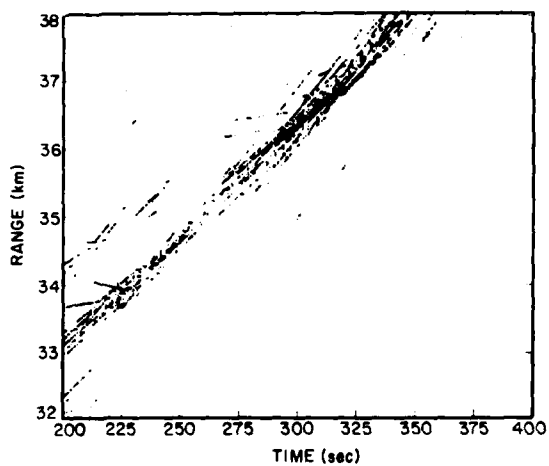
Knowledge of foliage and certain target characteristics can aid in arranging a flight plan for air-to-ground observation. An initial high-speed pass might alert the processing center of the presence of a moving target. Utilizing information such as target ground speed and direction of travel, a terrain-foliage data base could be accessed and an optimum visibility racetrack constructed and relayed to the aircraft.

A moving target may stop or change course at any time. If either event occurs during a period of masking, the continuity of the track is lost. An optimum racetrack could reduce or eliminate the probability of error due to target report drop-outs.

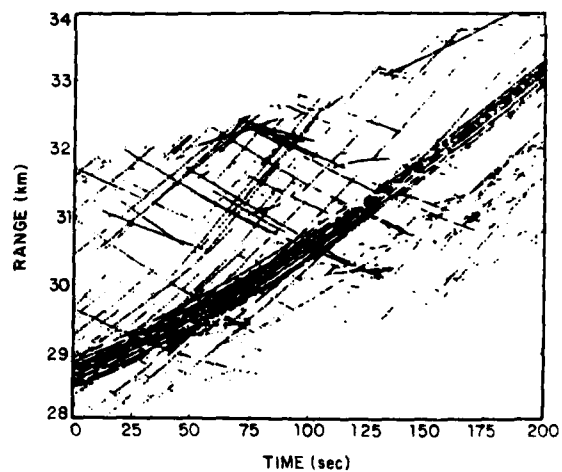
Again considering scenario A, it is a simple calculation to determine a 100% visibility orbit for Route 2. Referring to the skyline tracings, azimuths with a clear LOS at 6° elevation angle were noted for each road segment. In order to insure that the line-of-sight was never blocked, for this road the stipulations were: The aircraft had to be at +5° (107 km from the start of the racetrack) azimuth with respect to the vehicle



(a)



(b)



(c)

Fig. 22. Range vs time plot of convoy on Route 495.

at an elapsed time of 283 seconds; in the remaining 148 seconds of flight time on the data leg, the aircraft could travel no more than 7° (19 km) azimuth. For 100% visibility, an aircraft traveling at 400 mps at the start of the data leg reduces speed by .65 meter per second per second until after 283 seconds it has decelerated to the minimum velocity of 216 mps. The remaining 19 km of the racetrack are travelled at this constant velocity. Figure 23 illustrates the data leg of this racetrack.

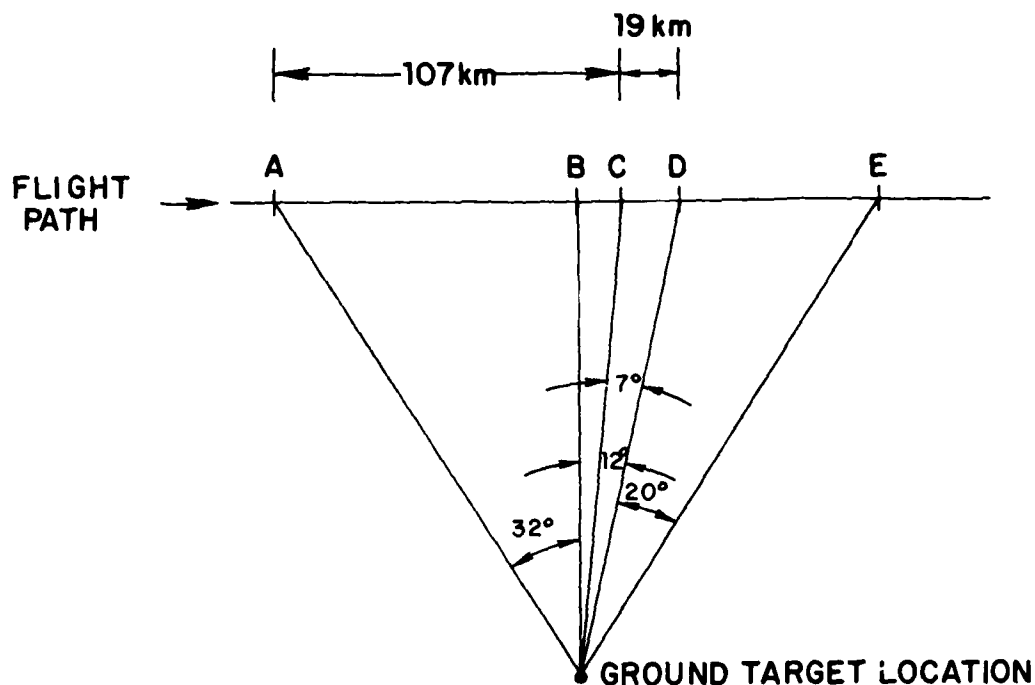
IV. CONCLUSIONS

The data presented in this report give conclusive evidence that foliage shielding does exist for air-to-ground L-band radar. Figure 24 is a map of Route 2, superimposed with actual MASR test data. The photographs in the lower portion of the figure show the skyline for the designated section of road. This data gives a simple but dramatic view of how foliage adversely affects target visibility.

The Route 495 experiment shows that foliage shielding can be predicted with some degree of accuracy. Foreknowledge of foliage characteristics aids in determining the most appropriate method of radar observation, whether ground-based or airborne. At the very least, target tracking parameters can be adjusted if report drop-outs are expected.

Admittedly, the method of data collection and analysis done here would not be feasible on a large scale. Probably the most reasonable approach is one mentioned before, annotation of terrain data with vegetation heights. If standoff surveillance of roads is to be done, several parameters must be considered in collecting vegetation data.

First, a mean tree height can be calculated and added to the terrain elevation for an entire area. However, as pointed out by V. L. Lynn, resolution of the areas being mapped must be of an order equal to a fraction of the road width. Figure 25 is an exaggerated example of shielding and clear LOS for the same tree height at different distances from the road. Even though the proportions are not to scale, it can be



- A: -32° AZIMUTH
START OF DATA COLLECTION
INITIALIZE DECELERATION FOR MAXIMUM VISIBILITY
- B: 0° AZIMUTH
CENTER POINT OF NORMAL (A to E) RACETRACK
- C: $+5^\circ$ AZIMUTH
END DECELERATION, START OF CONSTANT VELOCITY PORTION
- D: $+12^\circ$ AZIMUTH
END OF OPTIMUM RACETRACK
- E: $+32^\circ$ AZIMUTH
END OF NORMAL RACETRACK

Fig. 23. Maximum visibility racetrack for Route 495.

FOLIAGE SHIELDING

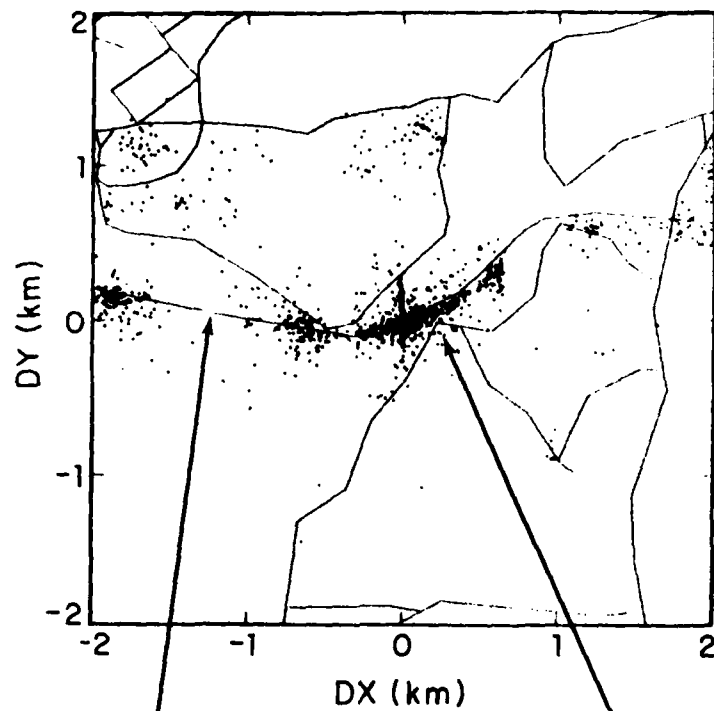


Fig. 24. Evidence of shielding in MASR data Route 2.

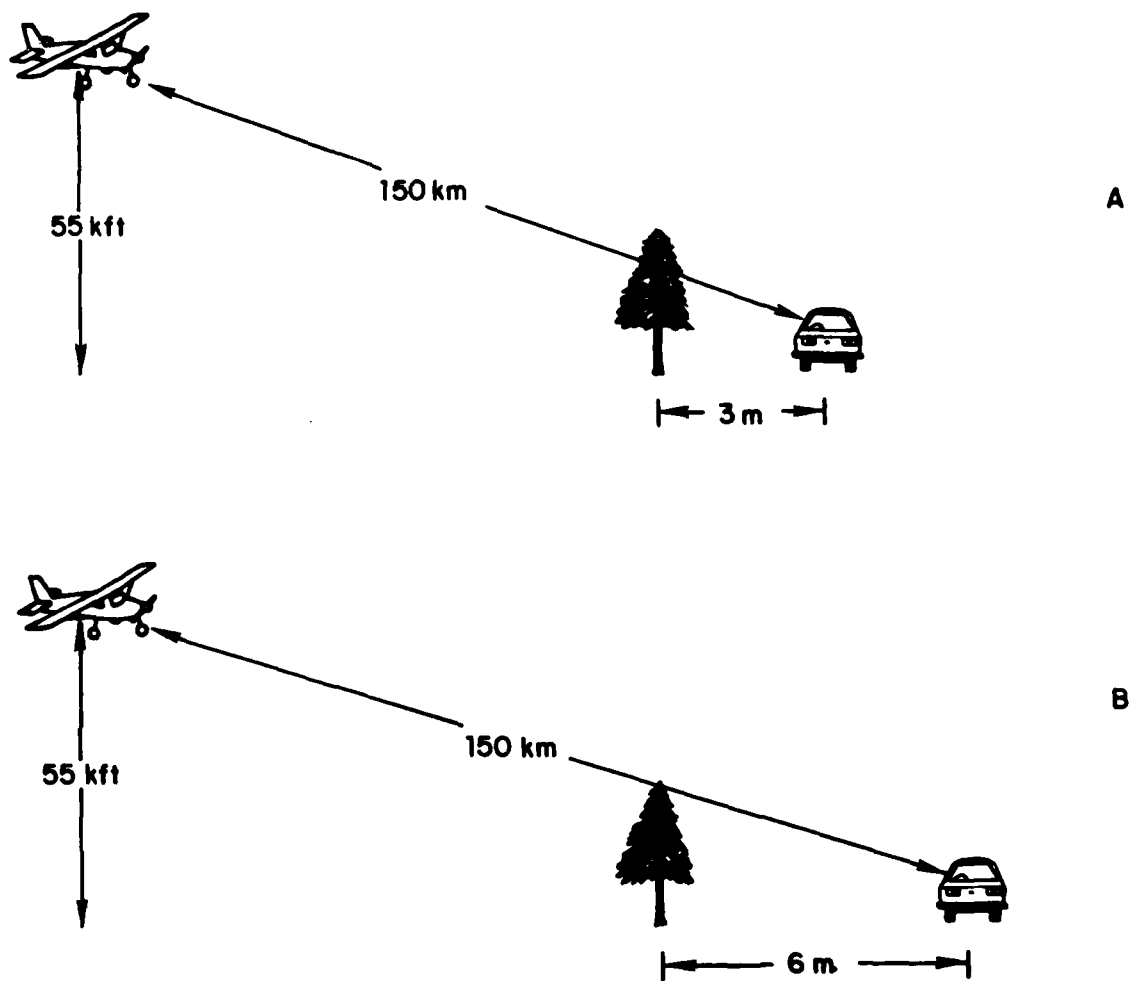


Fig. 25. Visibility relative to distance between target and obstruction.

seen that the distance from the tree line to the target is important and should be known to within several meters.

Second, vegetation grows from year to year. It would be possible to allow for an annual growth rate for each genre of vegetation, updating the data base at appropriate intervals.

This analysis attempts to cover only one aspect of foliage effects, total shielding of targets. Not considered were diffraction or attenuation due to foliage. Further research supplemented with experimental data would add depth to our present knowledge of foliage on target visibility.

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W. B. Goggins was instrumental in the design and planning of this experiment. His ideas and critical comments aided greatly in the analysis. P. F. Murray collected most of the raw data and also maintained invaluable records of all data-gathering missions. J. H. Mahoney supplied all the exacting photographic work. The suggestions of M. L. Stone and D. F. DeLong added perspective and are gratefully acknowledged.

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1. V. L. Lynn, "Terrain and Foliage Masking for Long-Range Surveillance; A Sample of Measurements in Central Germany," Project Report TST-35, Lincoln Laboratory, M.I.T., (15 June 1979), DDC AD-B040205.
2. C. J. Burge and J. H. Lind, Line-of-Sight Handbook (Naval Weapons Center/China Lake, California NWC TP 5908 1977)

APPENDIX

Statistical Models
and
Skyline Profile Samples

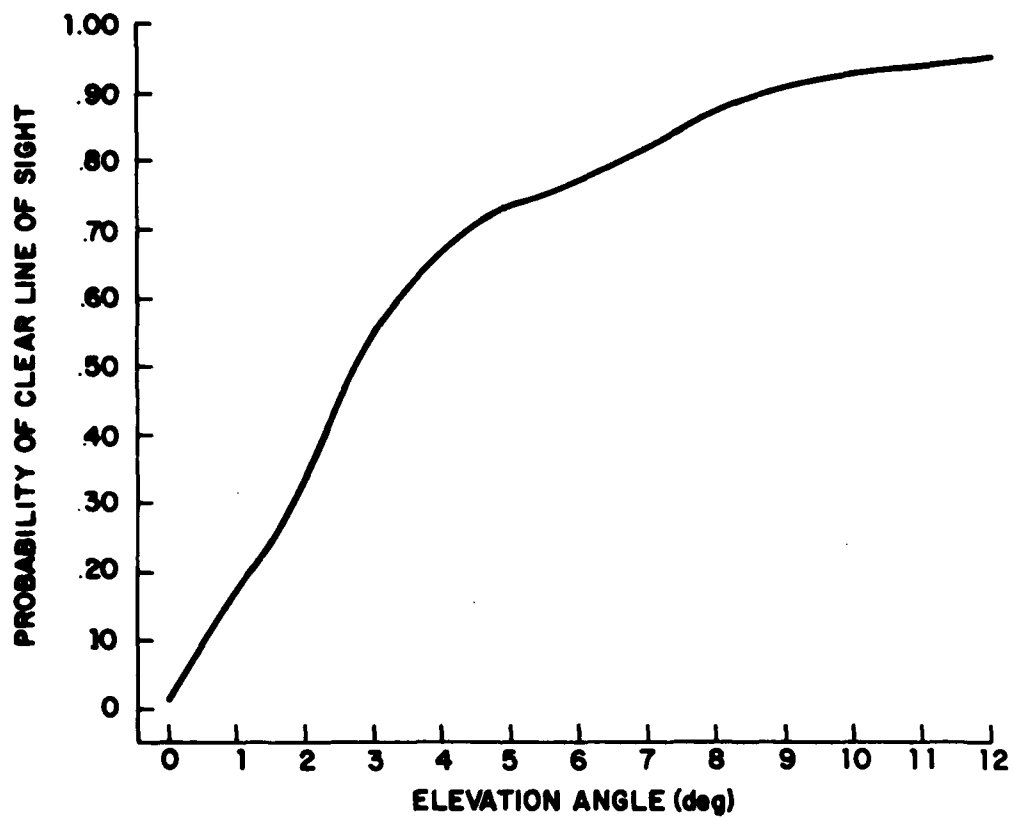


Fig. A-1. Route 2: A .5 probability of clear LOS occurs at 2.5° elevation angle.

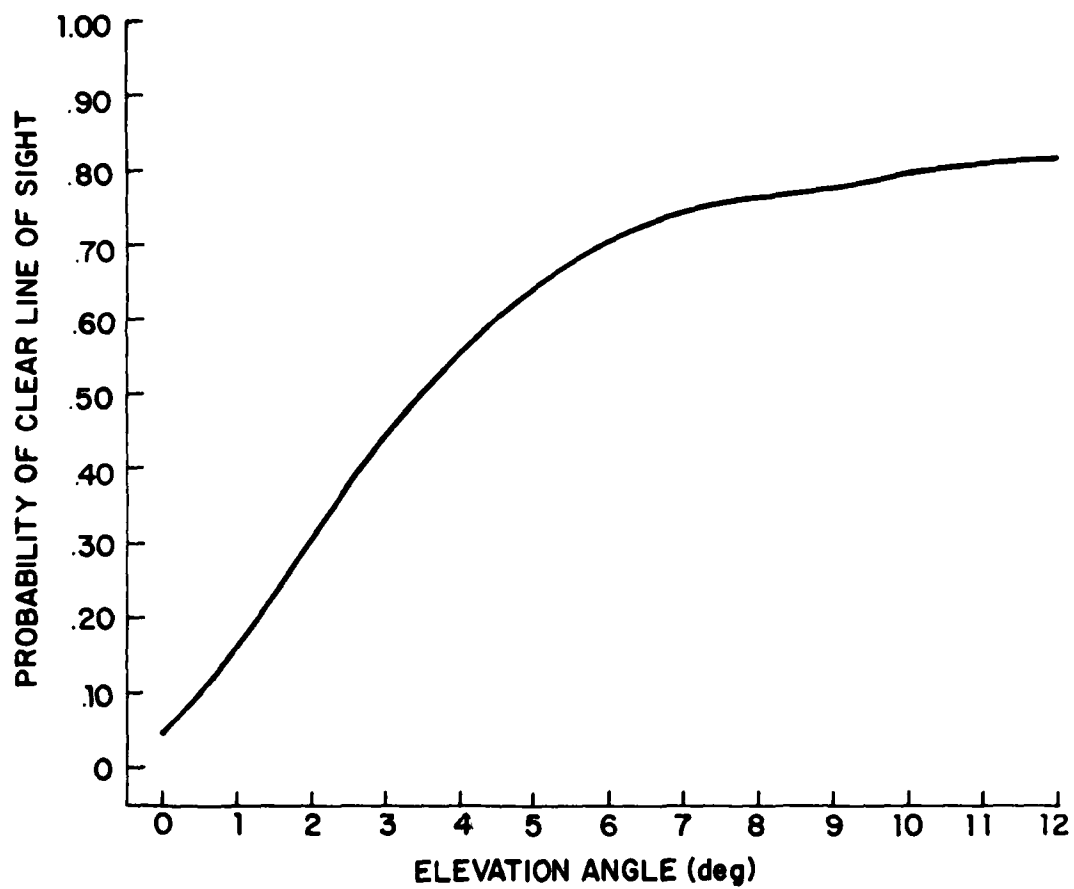


Fig. A-2. Route 495: A .5 probability of clear LOS occurs at 3.5° elevation Angle.

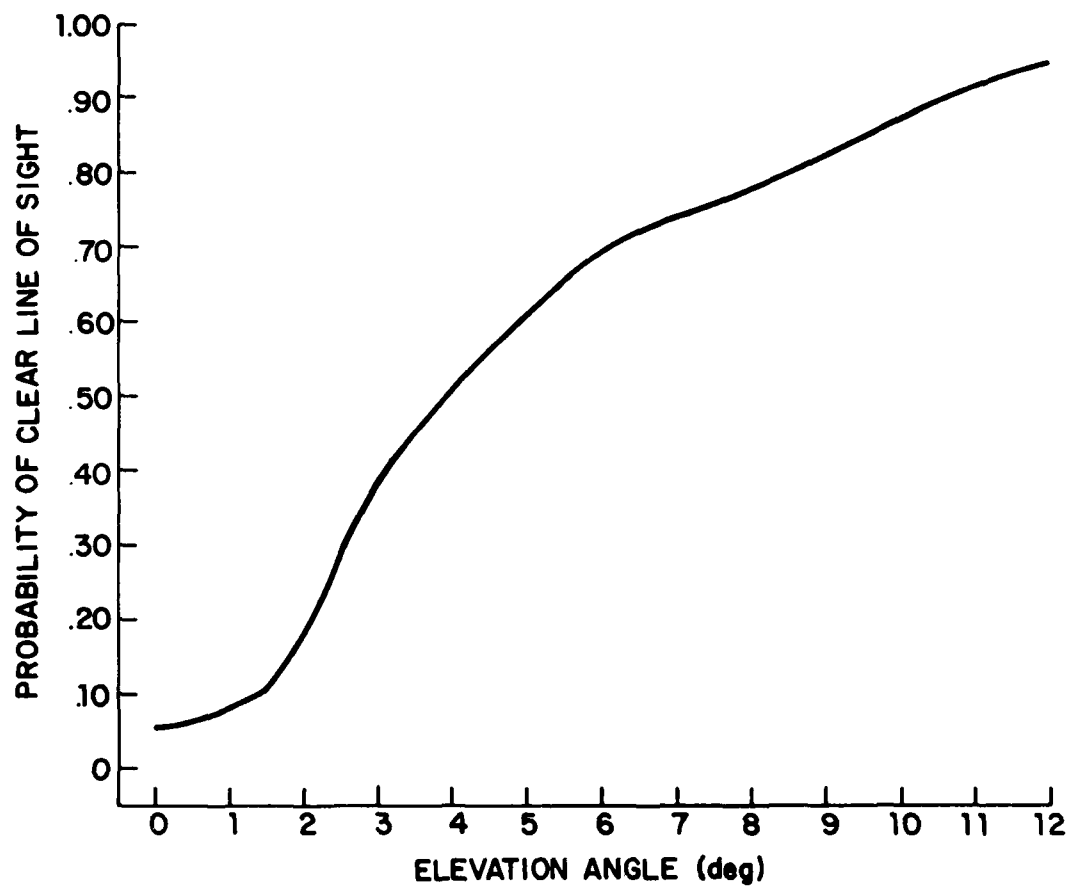


Fig. A-3. Route 90-east: A .5 probability of clear LOS occurs at 4° elevation angle.

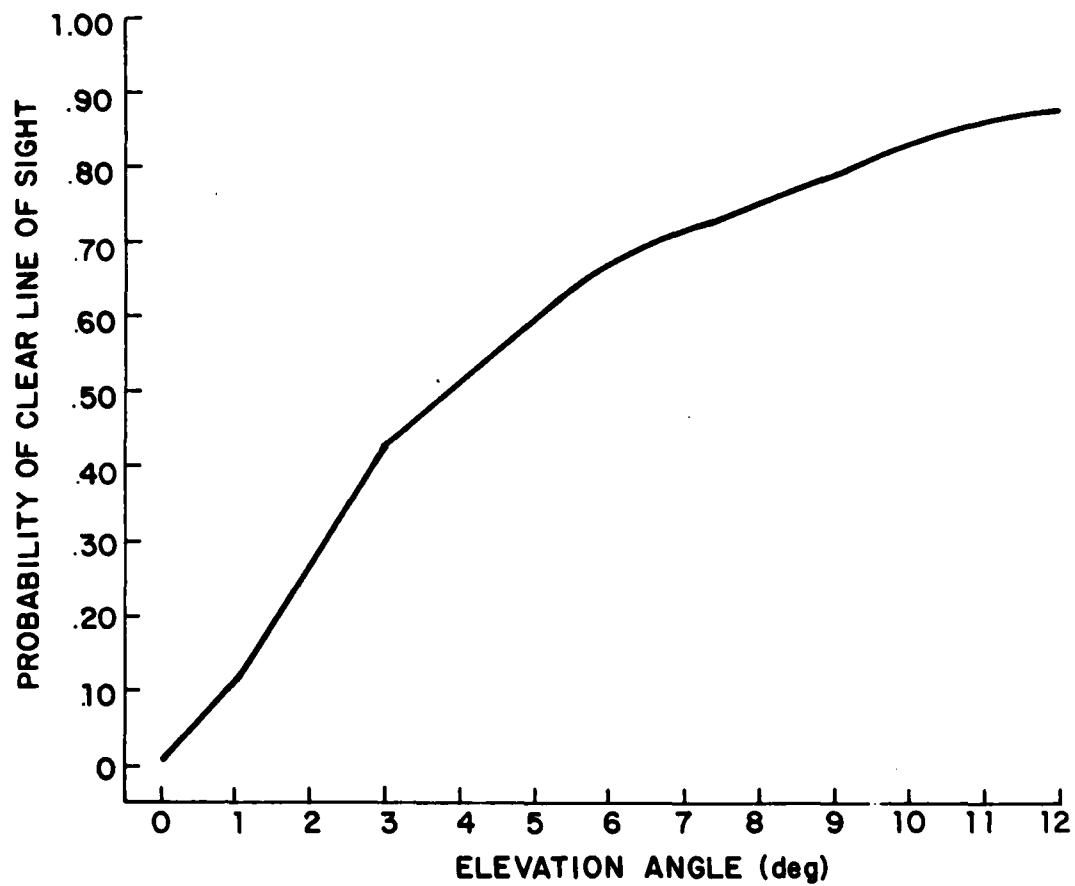


Fig. A-4. Route 90-west: A .5 probability of clear LOS occurs at 4° elevation angle.

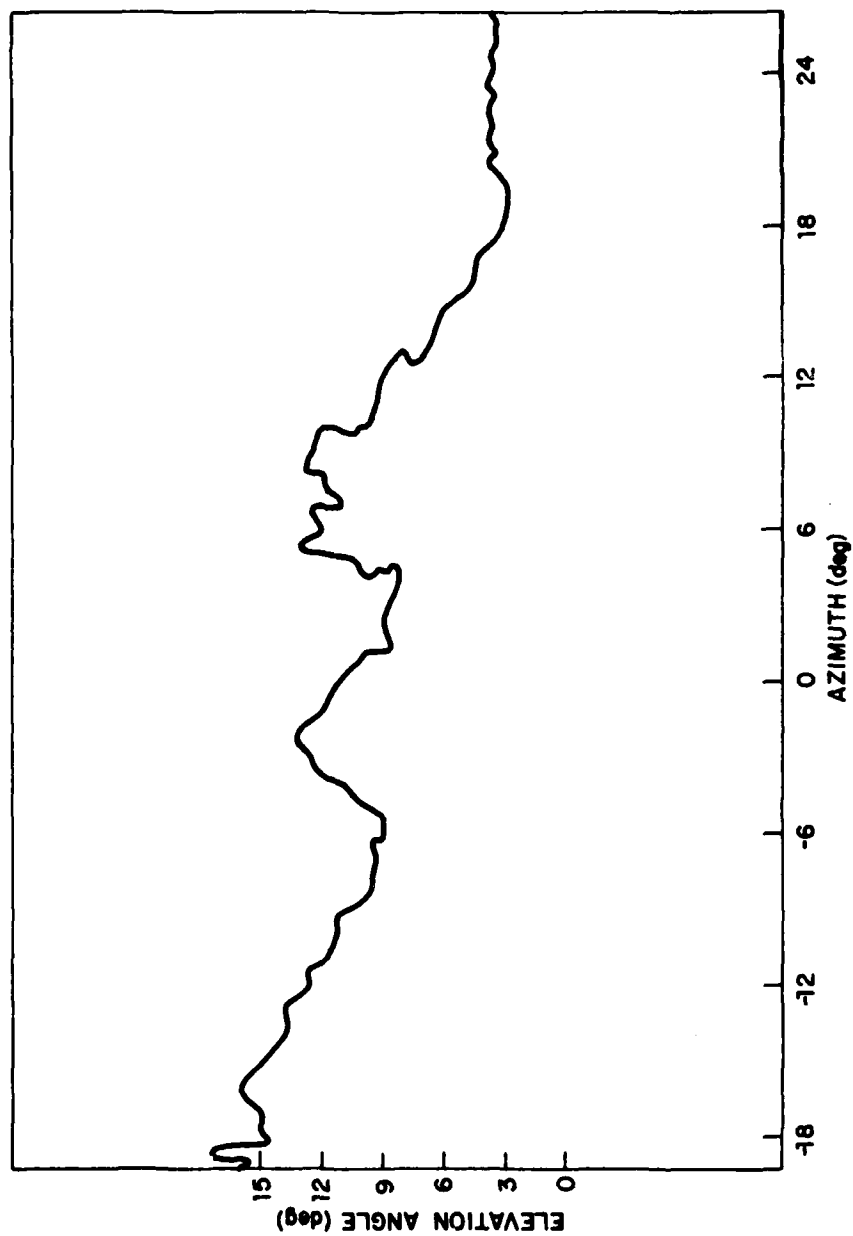


Fig. A-5. A skyline tracing for Route 2 in which the line-of-sight is obstructed for most elevation angles.

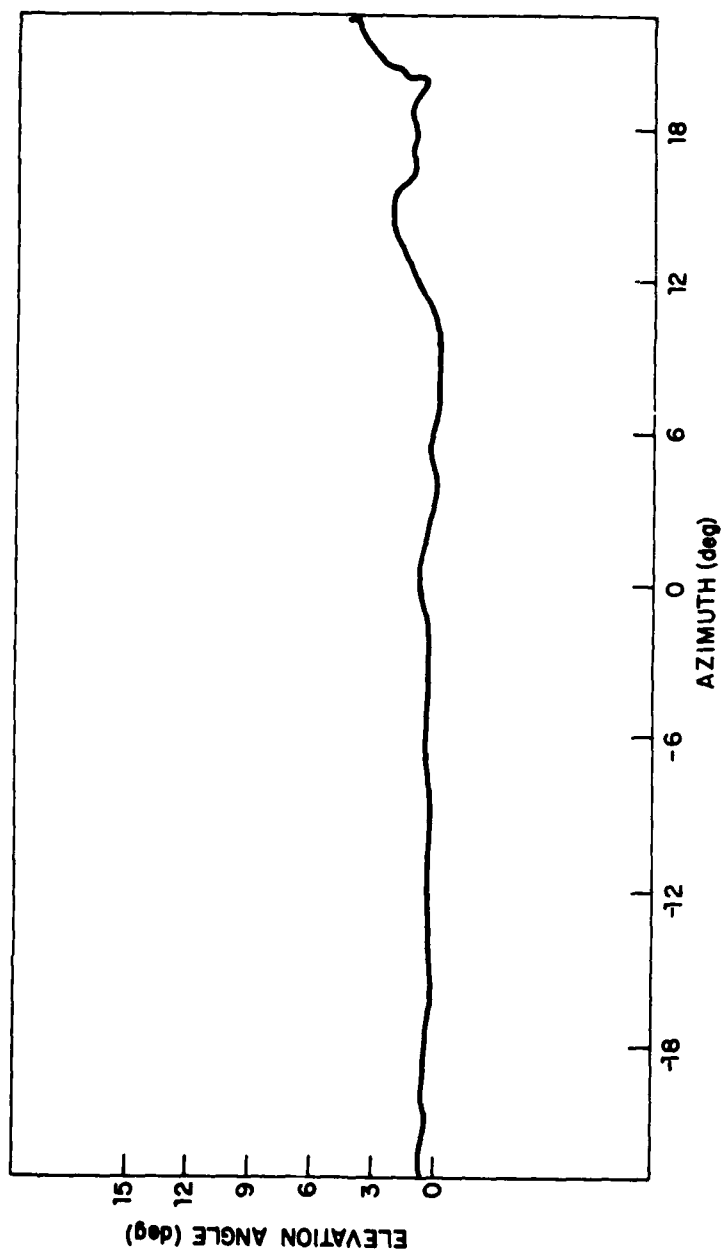


Fig. A-6. A skyline tracing for Route 2 in which a clear line-of-sight exists for most elevation angles.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report adds perspective to the problem of foliage shielding. Measurements were taken at four locations along three major eastern Massachusetts highways. Analysis results are compared with data from Multiple Antenna Surveillance Radar (MASR) tests. Probability of clear line-of-sight and period of target visibility are the major topics addressed.			

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